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The relative utility of current observation systems to global-scale NWP forecasts

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SUMMARY

We study 20 cases in which 60-hour forecasts of specific synoptic events have been markedly improved by observations made during the final 15 hours prior to the forecast initial time. For each case, the observing systems which played major rôles in improving the accuracy of the forecast mean-sea-level pressure (PMSL) field are identified using a series of Observation System Experiments (OSEs). The relative utility of each observation type is then assessed according to the frequency, over all cases, with which it delivers a major beneficial impact.

The method of multiple case study employed has the advantage that observation value is assessed according to the benefit delivered to forecasts of events (e.g. cyclogenesis) which are of prime importance to operational meteorology. The method therefore provides a useful complement to the conventional statistical approach which typically yields an "average" benefit, calculated for all regimes (both active and "quiet") occurring over a given period within a specific geographical region. The cases are selected from the most significant data impact events detected in routine operational forecasts of PMSL, for Europe and North America, during the period September 1993 to December 1995.

Results indicate that, for weather systems developing over North America, radiosonde and aircraft reports contribute major forecast benefits most often, confirming their key rôle in the North American network. These two observing systems contribute with similar frequency, suggesting that the effectiveness of the less abundant radiosonde reports is boosted significantly by their profile format. Surface data and cloud-track winds are the next most frequent contributors.

For weather systems developing over the North Pacific and North Atlantic, aircraft winds contribute forecast benefits most frequently, and by a wide margin. Conventional surface data also play a key rôle.

Comparison of the utility of wind and temperature data suggests that, on average, the benefit of wind profiles is somewhat greater than that of temperature profiles and that, in levels above ~400 hPa, wind data are considerably more valuable than temperature data.

The results give insights which can be used to guide the rationalisation of existing networks within the Northern Hemisphere mid-latitudes, and the following recommendations are made with a view to improving NWP forecasts over the European area;

- Acquire more aircraft data over North Atlantic routes and over Europe (including reports on climb and descent). However, caution must be exercised if aircraft data are used to replace profile information from radiosondes.
- Deploy more surface observations (e.g. drifting buoys) and ship-borne radiosonde ascents (ASAPs) over the North Atlantic.
- Make more use of pattern tracking techniques for deriving "clear air" wind data from satellite water vapour imagery.
- Continue investigation of the effectiveness of observations "targeted" on objectively defined regions where model errors are predicted to grow most rapidly.

1. INTRODUCTION

(a) Background and aims

An understanding of the relative utility of current observing systems to Numerical Weather Prediction (NWP) models is important to help make effective use of resources for observation. Information on the relative benefit of existing observation types is needed to optimise the design of the current composite network, and can provide insights which help in setting priorities for proposed new systems.

Much published work on observing system impact has concentrated on the evaluation of single observing systems, rather than on assessment of the relative utility of all current systems. This circumstance reflects operational practices at most NWP centres, where impact studies are generally performed to validate techniques developed to assimilate a new source of data (often a satellite-borne instrument), or to improve the assimilation of existing data, rather than to address questions of network design. Although studies of relative benefit were performed after the Global Weather Experiment in 1979, one objective of which was to design an optimum composite observing system (see, for example, Gilchrist, 1982), recent studies are few - examples being the work of Atlas (1997) and Kelly (1997), who compare the impact of a number of satellite and conventional systems. In addition, a collection of recent work and a consensus summary of observation value for short and medium range NWP forecasts may be found in Pailleux (1997).

In this paper we describe a method for assessing observation value based on accumulating results over a number of case studies (extending work by Graham, 1994). The method is applied to give an assessment of the relative utility of all current observing systems (conventional and satellite) commonly used in NWP models. We concentrate on identifying the observation types that play major rôles in improving the accuracy of 60-hour forecasts of PMSL. Twenty cases are studied and sample the most significant data impact events detected in routine operational forecasts, for Europe and North America, during the period September 1993 to December 1995. The cases include examples of impact from data over the North Pacific, North America and North Atlantic and results are therefore expected to be broadly valid for the Northern Hemisphere mid-latitudes. All cases are classified as either North American, North Atlantic or North Pacific type according to the geographical location of the impact source. The assimilation scheme and NWP model used are the UK Met. Office Analysis Correction (AC) scheme (Lorenc et al, 1991) and the global configuration of the UK Met. Office's Unified Model (Cullen, 1991).

(b) Overview of method

The method used has some novel features. Briefly, the approach is based on case study assessments of forecasts known to be sensitive to "recent" observations, where "recent" observations are those made during the final 15 hours prior to the forecast. Results are accumulated over all cases. Analysis of the cases is designed to address the question; "when recent data have a marked impact on the forecast, which data types are most frequently the source of that impact?". An overview of the method and comparison with more commonly used methods is given below; a detailed description is provided in Sections 3&4.

All data impact studies (or Observing System Experiments, OSEs) comprise a sample of cases over which forecasts from a control (or reference) integration are compared with experimental integrations in which the data assimilated are varied relative to the control (see e.g Atlas, 1997). The method used here differs from standard methods in the selection of the sample of cases, in the definition of the control and experiment integrations and also in the form of the impact assessment. The nature of the differences and their implications are summarised below.

i) Choice of cases and assessment method: In the multiple case study method employed here, the cases studied comprise a series of non-consecutive forecasts (10 cases each for Europe and North America), selected from the most significant data impact events detected in routine operational forecasts. The geographical area of assessment is not fixed, but varies within each region according to the location of the feature of interest in the case. The relative utility of each observation type is assessed according to the frequency, over all cases, with which it delivers a major beneficial impact (see Sections 3&4 for a definition of "major"). In contrast, the cases studied in the more usual method of impact assessment comprise consecutive forecasts typically 14, i.e. one per day for a 2 week period), where the period is chosen, at best because it has meteorological interest (though not necessarily because there is evidence of data impact), but frequently for reasons of technical convenience (e.g. a control run for the period may already be available, thus saving computer resource). Observation benefit is typically presented in statistical form (e.g. improvement in anomaly correlation or rms error) over a specific geographical region over the full experiment period. We shall refer to the latter approach as the "statistical" method to distinguish it from the multiple case study approach.

The main advantage of the multiple case study approach is that observation benefit is assessed according to the benefit delivered to forecasts of significant synoptic-scale events (e.g. cyclogenesis), which are of prime importance to operational meteorology. In contrast, statistical evaluations of performance over specific regions and periods, can result in important impacts on individual features being masked by negligible impacts during long "quiescent" spells. The main criticism levelled at case studies, namely the lack of generality in results, is addressed by analysis of a similar number of cases as typically used in statistical studies. A further advantage of the approach used here is that a null impact, arising through unlucky selection of the study sample, rather than through any intrinsic value of the data, is avoided; all cases chosen are known to be sensitive to some element of the initial data.

ii) Choice of assimilation period: In the approach used here, in which we are chiefly concerned in identifying the data type responsible for an improved forecast, the assimilation period used in each case study, for control and experiment, is relatively short. A short assimilation suffices since the observed impact is known to have been imparted by observations made within 15 hours of the forecast initial time. The above method contrasts with the statistical approach in which the control and experiment assimilations are run continuously over the entire experiment period. Since the forecasts are consecutive this is an obvious and convenient approach,

it also has the advantage that cumulative impacts accruing over an extended period are evaluated.

Cumulative impacts are not assessed by the multiple case study method. Consequently, the technique is weighted towards measuring the utility of observations for the analysis of systems with a Eulerian timescale comparable to 15 hours (i.e. synoptic-scale phenomena), rather than value for specifying the more slowly varying larger-scale flow patterns. This is not considered a disadvantage, because of the great importance of synoptic-scale systems to weather prediction. However, it should be noted that the utility of observations more suitable to specification of larger-than-synoptic scales may be underestimated (see Section 6 for a discussion). As such we consider the multiple case study method a complement rather than an alternative to the standard statistical approach, in which the impact of both recent and historical data is evaluated.

iii) Experimental strategy and choice of control: Most published data impact studies use the "data denial" method, in which all available data are supplied to the control assimilation, while the experiment integration is supplied with all the available data minus a certain data type (or types). Comparison of the ensuing forecasts gives the impact of the data withheld in the experiment. Here we employ a different approach, which by analogy to "data denial" may be referred to as a "data addition" method, in which the control forecast is produced from a dummy assimilation in which no observations are assimilated (referred to as the NO OBS control). In each experiment a single data type or a limited combination of data types is supplied to the assimilation. Comparison of the control and experiment thus measures the impact of a data type (or types) against a baseline forecast obtained using no observations in the preceding short assimilation period.

The data-denial method essentially serves the operational practices referred to in the previous Sub-section in that it measures the degree to which an observation type adds value to the overall network, and thus provides a benchmark for inclusion (or otherwise) of a new data type into an operational assimilation. For issues of network design, however, it is also useful to have to a measure of the individual impact of a data type, regardless of its redundancy with respect to the full network, since part of the aim is to compare the value of observation types which may be mutually redundant in order to decide which type should have priority in the network. The data-adding method, against a "no observations" control provides a basis for this comparison. Moreover, once the observations which are most effective singly are identified, their benefit when combined may be assessed and compared with that of the full network.

Details of the case selection method are given in Section 2. The data impact experiments performed on each case and the method used to accumulate information over all cases are described in Sections 3 and 4. Results on the utility of the various observation types, and an assessment of the relative utility of wind and temperature profiles are given in Section 5. Conclusions are summarised in Section 6, which contains a discussion of results. Recommendations for the Atlantic/European composite network, aimed at bringing improvements to NWP forecasts over Europe, are made in Section 7.

2. CASE SELECTION AND CLASSIFICATION

(a) Case selection

The selection method is based on identifying cases in which recent data have had a marked impact on operational forecasts. This is achieved by looking for unusually large local differences in operational 72-hour and 60-hour PMSL forecasts, valid for the same time. Large differences indicate a significant data impact from the additional data available to the later 60-hour run. Two geographical regions (shown in Fig.1) are checked for forecast differences. The first incorporates much of North America, the second incorporates Europe and western Asia. Although each area includes some ocean, only forecast differences over land are considered. The density of surface observations over the major part of these regions is relatively high and hence we have reasonable confidence in the accuracy of the objective analyses used to assess the data impacts. Only impacts on systems forecast to be located in either of these two areas at T+60 or T+72 are considered for study.

Cases are short-listed for study if the maximum absolute difference in forecast PMSL, over either selection region, exceeds a predetermined threshold. The thresholds values are arbitrary, and were selected to provide a manageable number of cases for subjective filtering. For the North American region the threshold was set at 20 hPa, this resulted in a short-list of 29 cases out of a total of 1360 60-hour and 72-hour forecast "pairs" for the period (slightly shorter than the full period of the study) January 1994 to December 1995 (Global Model forecasts are run twice daily from analyses at 00GMT and 12GMT). The short-list represents the largest ~2% of all data impacts (assuming there is some impact from recent data in all cases). For the European region the threshold was set at 12.5 hPa, resulting in a short-list of 121 cases (representing the largest ~9% of data impacts for the period).

Final selection is performed subjectively. Only cases of positive data impact (60-hour forecast better than the 72-hour forecast) were selected for study, though negative impact was found in a minority of cases. Cases in which the two forecasts show marked differences in evolution, rather than small positional differences in an intense feature, were given preference.

(b) Classification of cases

The relative number of observations from the different observing systems used in the model varies greatly between land and ocean. For example TOVS temperature soundings and scatterometer winds dominate over the North Pacific and North Atlantic, while observations from aircraft and radiosondes dominate over North America (Table 1). Since the abundance of an observation type will clearly influence the frequency with which it gives beneficial impact, it is necessary to perform separate assessments of relative utility for land and ocean areas. Each case is therefore classified according to the geographical location of the impact source, as a "North Pacific", "North American" or "North Atlantic" type - these regions broadly covering the initial location of systems which affect the case selection areas of North America and Europe (Fig. 1) some 2-3 days later.

The location of the impact source is estimated by identifying differences in the forecast upper-level potential vorticity (PV) structure that are diagnostically associated with the main differences between the 60-hour and 72-hour PMSL forecasts (using the PV perspective of Hoskins et al., 1985). The PV differences are traced back through the forecast to the assimilation phase where their position gives an estimate of the general area containing the data which imparted the observed benefit. In cases where results of the PV tracing were ambiguous, or when it was suspected that downstream development was important, the location of the influential data was confirmed by performing impact experiments in which only data from the suspected region were included in the assimilation. It was found in practice that impacts initially imparted at low levels (e.g. from surface data) usually propagate quickly (within 24 hours) to the upper-level PV fields. Consequently reference to the PV structure at a single upper level ($\sim$315K) was found sufficient to identify the approximate geographical location of impacts initially imparted at either high or low level. In cases where observations from widely different regions appeared to have been involved in the impact, classification was made according to the region considered (subjectively) to be the more important.

(c) Cases studied

The twenty cases studied comprise ten North American cases, seven North Atlantic cases and three North Pacific cases. The date of each case (identified by the verifying time of the T+60 and T+72 forecasts), and a brief description of the main feature improved in the T+60 forecast are given in Table 2.

3. METHOD

(a) Forecast experiments

A series of Observation System Experiments (OSEs) are conducted for each case, with the aim of determining which observation type or types delivered the major part of the impact detected in the case selection procedure. The value of each observation type may then be assessed according to the frequency, over all cases, with which it delivers major impacts. All experiments involve a 72-hour integration of the Global Model initiated from a common analysis. Observations valid for the first 15 hours of the integration are inserted using the UK Met Office Analysis Correction (AC) scheme, which is based on a "nudging" technique. Assimilation of all observations is completed after 16 hours of integration ("nudging" continues for 1 hour after the valid time of the observation). The remaining 56 hours of integration are run in forecast mode (the forecast is referred to nominally as a 60-hour forecast from the last main synoptic hour of the assimilation period, i.e. either 00GMT or 12GMT).

Two control experiments are run. One uses all the available data in the assimilation (the ALL OBS run); the other entails a dummy assimilation using no data (the NO OBS run). The ALL OBS and NO OBS runs correspond, respectively, to the later "more skilful" operational forecast and the earlier "less skilful" operational forecast identified in the selection procedure.

The benefit of the data to the PMSL forecast is measured according to the

reduction in root-mean-square error, achieved relative to the NO OBS control, over an area enclosing the feature of interest. The evaluation area is chosen so that it encompasses the main regions of 60-hour and 72-hour forecast error - typically the area might include both the positive and negative poles of an error dipole associated with a poorly positioned depression (An example is given in Section 4.).

(i) Runs using single data types: To identify the data types which contribute to the observed impact we first perform a series of runs in which only a single data type is presented to the assimilation. The impact obtained with a single data type is referred to as the "individual" impact from that type. The individual data types assessed are shown in Table 3. With the exception of surface reports, the benefit of each variable reported by an observing system is assessed separately (e.g. wind, temperature and humidity for radiosondes reports). For surface reports, the combined benefit of PMSL and wind observations is assessed. Restrictions on the use of data within the model will clearly have an impact on the potential benefit, and are indicated in the table (for more details the reader is referred to Bader (1995).

The single-data-type runs give useful insight as to which data types play key rôles in the observation network. Moreover, they give a measure of the relative benefit of data types between which some redundancy would normally be expected and thereby give an idea of which type should have priority in the network. This issue is less easily addressed using the data-denial method - since a "potential" impact from the data type withheld will not be registered if a similar impact is imparted by one or more of the other data types assimilated.

(ii) Runs using combinations of data types: In addition to the single-data-type runs, the impact of combinations of observation types is also addressed to allow the effects of redundancy and synergy to be taken into account. The aim of the combined data runs is to identify, for each case, the smallest subset of data types required to deliver at least 90% of the benefit obtained when all data types are used. Results of the single-data-type runs are used to help construct the subset (referred to as the "90% subset"). The data types which form the 90% subset are also ranked (from 1 to 4) in order of cumulative benefit. The benefit of a data type may then be assessed according to the frequency and rank of its inclusions in the 90% subset.

Ideally, we would like the 90% subset to be unique; however, to ensure uniqueness would require assessment of the forecast skill obtained with all possible combinations of data types. Such an approach would require a great many model runs and is not a practical option. We have therefore adopted a simplified method in which the search for the 90% subset is guided by the individual benefit of each data type. The assumption made is that the data type with the largest individual benefit is also the rank 1 member of the 90% subset. The method is described in detail with the aid of an example case in Section 4.

4. DETAILS OF THE METHOD: AN EXAMPLE CASE

In this section we describe details of the procedure for finding, for each case, the individual impacts of each data type, and the 90% subset. As an aid we shall refer to results from Case 10 - a cyclogenesis event which occurred over eastern Canada during November 1994 (Table 2). For a shorter read, this Section may be skipped without impairing a general understanding of later Sections.

The PMSL analysis for 12GMT 2 November 1994 over eastern North America is reproduced in Fig. 2 and shows a low of central pressure 989 hPa located between the Great Lakes and Nova Scotia. The corresponding NO OBS forecast, shown in Fig. 3a, has a considerable error in the location of the depression which has been placed over Newfoundland, some 14° ENE of its true position. The intensity of the depression is also too weak in the NO OBS forecast, with a central pressure (999 hPa) some 10 hPa too high. Differences from the verifying analysis are shown in Fig. 3b and show errors reaching 27 hPa near the true position of the low. The corresponding forecast from the ALL OBS control run is shown in Fig. 4a. Comparison with the analysis (Fig. 2) shows that the ALL OBS forecast was a very good one, both in terms of position and intensity. The forecast location is very close to the true position and the central pressure of 992 hPa is correct to within 3 hPa. Reference to the error in the ALL OBS forecast shown in Fig. 4b shows that the magnitude of PMSL errors in the vicinity of the low is generally below 3 hPa.

(a) Assessing the individual impact of data types

A model run is performed for each of the 9 data types shown in Table 3, in which only that data type is presented to the assimilation. To avoid pre-judging the precise source of the data impact, all observations of the specified type (world-wide) are assimilated. A table of the individual benefits of all 9 data types is thus produced for each case. Individual benefits for Case 10 are shown in Table 4, with data types listed in order of decreasing benefit (i.e. increasing root-mean-square error over the area delineated in Fig. 3b).

Substantial individual benefits, ranging from ~30-50% of the benefit obtained with all the observation types (the "ALL OBS" benefit) were obtained with aircraft and radiosonde observations of wind and temperature. Only small benefits (7% or less) are derived from the sole use of surface data, radiosonde humidities or cloud track winds. Satellite temperatures are not used in the assimilation over land areas below 100 hPa (Table 3) and, since the cyclogenesis occurred over North America, the 17% benefit from this data type must derive either from a downstream effect or, perhaps, from observation of inflowing air, ahead of the incipient depression, off the east coast of North America. Similarly, scatterometer observations of the 10 m wind field can only have an indirect impact on this case, and the small impact observed is therefore not surprising.

In this example the ALL OBS and NO OBS control runs have, respectively, the highest and lowest forecast skill. This is not true of all cases, however, some of which have shown negative impacts from some data types (these types would consequently be placed lower than the NO OBS run in the benefit ranking).

(b) Finding the 90% subset

To find the 90% subset we follow a two step process illustrated in Tables 5a-c, again using results from Case 10 as an example. In the first step (Table 5a), a number of model runs are performed introducing one additional data type to the assimilation in each successive run. The first run is the run (already performed), in which the data type with the largest individual benefit is assimilated (aircraft winds in this example), in subsequent runs data types are added in order of their individual benefit until 90% or more of the ALL OBS benefit is achieved. In this example the first six data types in the individual benefits table (Table 4) are required before the combined benefit exceeds the 90% threshold (actual benefit achieved = 99%). These data types represent a first estimate of the 90% subset, which is refined in the second step.

In step two we attempt to reduce the number of data types in the 90% subset. This is achieved by removing those types which make the smallest increments to the combined impact until the benefit obtained falls below the threshold of 90%. In Table 5a the three data types giving the smallest increments as they are added in turn are satellite temperatures (2%), radiosonde winds (7%), and surface data (10%). The result of successive removal of these data types from the subset presented to the assimilation is illustrated in Table 5b. On removing satellite temperatures the benefit remains above 90% of the ALL OBS benefit. The benefit remains above 90% when both satellite temperatures and radiosonde winds are removed (in fact the benefit increases by 1% - suggesting that a degree of conflict exists between radiosonde winds and the remaining data types). However, on removal of surface data the benefit drops below the threshold to 84%. The final 90% subset therefore comprises aircraft winds, aircraft temperatures, radiosonde temperatures and surface data (Table 5c).

The forecast obtained when only these four data types are included in the assimilation is reproduced in Fig. 5a. The great similarity with the ALL OBS control forecast (Fig. 4a) confirms that use of this subset of the data alone is sufficient, in this case, to reproduce the significant part of the benefit obtained when all the observations are used. The similarity in the forecasts may also be appreciated by noting the few differences in the error fields of the ALL OBS and 90% subset runs (Figs. 4b & 5b). (Near the low centre the error dipole in the 90% subset run is a little stronger than in the ALL OBS run - suggesting that the data not included in the 90% subset played a very small rôle in improving the position of the low).

Further runs are performed in order to rank the subset of data types in order of benefit. The data type delivering the largest individual benefit is assigned rank 1; rank 2 is assigned to the data type that delivers the largest increment to the benefit achieved with the rank 1 data type; rank 3 is assigned to the data type which gives the largest increment in benefit to that obtained with the rank 1 and rank 2 data types, and so on. The ranking order for the current example is shown in Table 5c. None of the twenty cases studied required more than 4 observation types to obtain 90% or more of the ALL OBS benefit. In 2 cases (4 and 9) more than 90% of the ALL OBS benefit was achieved with a single observation type.

Examples of both redundancy and synergy between data types can be seen by comparison of Tables 4 and 5c. Radiosonde winds deliver the second largest individual benefit (45%, Table 4), yet are not required in the 90% subset (Table 5c), presumably because of redundancy in combination with aircraft winds.

In contrast, surface data deliver the sixth largest individual benefit (Table 4), but are ranked third in the final subset (Table 5c), indicating a synergistic effect with either aircraft winds, radiosonde temperatures or both.

5. RESULTS

(a) Individual benefits, North American cases

Table 6a shows the individual benefits of each observation type (as a percentage of the ALL OBS benefit) for the 10 North American cases. The average benefit over all cases gives an estimate of the relative skill the forecasts would have if each observation type were the only type available, and therefore helps to identify the "mainstays" of the network. Over North America radiosonde and aircraft observations are relatively numerous (Table 1) and the abundance of these data is reflected in their high scores in the table. Radiosonde winds have the highest average individual benefit of 49%, suggesting that if used alone they would provide, on average, about half the benefit derived from all the available data.

A difficulty in interpreting the impact of wind reports arises because of the use of duplicate observations. A given wind profile may sometimes be received both as a PILOT and as a TEMP message. In such cases the report is used twice in the assimilation, effectively doubling the weight assigned to it. To check the impact of using duplicates, six of the ten experiments were re-run using only the TEMP wind messages. The results are given in brackets in Table 6a, and show that, with one exception (Case 10) the results are identical or similar - giving confidence to our assessment of an average individual impact of around 50% for radiosonde winds.

The radiosonde temperature profiles are somewhat less effective than the wind profiles, giving an average individual benefit of 24%. The difference in benefit most likely reflects an intrinsic advantage in the use of wind reports over temperature reports, as identified in theoretical studies (see e.g. Daley, 1980; Kalnay et al., 1985) and also in model assimilation studies with idealised simulations of wind and temperature data (e.g. Halem and Dlouhy, 1984; Atlas et al., 1985). However, other factors that may result in greater impacts from wind observations relative to temperature observations should be borne in mind. Firstly, model fields tend to take longer to adjust to temperature data than to wind data (see e.g., Kalnay et al., 1985), consequently our assessment which is based on a short assimilation period (16 hours, see Section 3(a)) may penalise the temperature observations. Secondly, the assimilation scheme itself may be better "tuned" for wind data than for temperature data. Differences in the distribution of the radiosonde wind and temperature reports are unlikely to contribute to their different impact, since the distribution will be identical except for cases where either the wind or temperature part of the report is missing or fails the model quality control process.

The wind and temperature parts of the aircraft reports show more similarity than the wind and temperature parts of radiosondes, with aircraft winds having an average individual impact of 38% (the second highest) and temperatures 34%. The average figure for aircraft temperatures is boosted by two cases (4 and 19) where aircraft temperature data on the east coast of the USA were extremely useful for

the T+60 forecast for western Europe. Further examination of Case 4 shows that, in this instance, the benefit of aircraft temperatures was imparted exclusively from reports below 500 hPa (i.e. from aircraft on climb and descent near airports in the eastern USA).

The average individual benefits of the remaining data types are substantially smaller than for the radiosonde and aircraft wind and temperature reports. Surface data, cloud-track winds and satellite temperature soundings each have an average individual benefit between 14% and 18%, while radiosonde humidities and scatterometer wind data have average benefits of 7% and 1%, respectively. Although satellite temperature soundings are not used over land below 100 hPa, and scatterometer winds are only available over the ocean surface, both may contribute to data impacts over North America by providing information in coastal regions or indirectly by downstream effects.

Cases of negative impact have been recorded in Table 6a, and affect all observation types except for the radiosonde winds. A negative impact does not necessarily imply that the data were inaccurate. For example, good quality well placed observations may, at a given time, result in the analysis of an upper trough (say) which is small enough to have missed observation at earlier times. If in the forecast the trough interacts with a spurious model feature (e.g. a poorly located baroclinic zone) the forecast may, locally, be significantly worse than if the trough had remained unobserved (and unrepresented in the analysis). Although some cases of negative impact are to be expected, all observation types should clearly have a positive impact on average. Frequent local negative impacts from a particular data type may therefore indicate problems with the use of that data by the assimilation scheme.

(b) Individual benefits, oceanic cases

The individual benefits for the 10 Oceanic cases (7 North Atlantic and 3 North Pacific) are shown in Table 6b. Over these oceanic regions aircraft observations and satellite temperature soundings are most numerous. Aircraft winds have the highest average individual benefit of 44%. In contrast to the North American cases, aircraft temperatures have a relatively low average individual impact (9%). The difference in impact between land and ocean may well reflect the different distribution of aircraft reports in those regions. Over the oceans the aircraft data is almost exclusively from cruise levels above 400 hPa, while over North America reports are also available below 400 hPa from climb and descent near airfields. The results for oceanic cases therefore suggest that use of temperature data at upper-levels only is of very limited value, while use of wind data at upper-levels only can be very effective. The greater benefit of aircraft temperatures over land compared to that over the ocean suggests that much of the impact from temperatures over land derives from the low level reports (evidence for this, in Case 4, has already been alluded to in the previous section) - suggesting that use of temperature data at low-levels is much more effective than use at upper-levels.

The average individual benefit for surface data is somewhat higher over the oceans (29%) than over land (18%, Table 6a). Reference to the individual cases (Table 6b) suggests that surface data can contribute significantly to cases of marked data impact over the oceans. Satellite temperatures and cloud-track winds

have average benefits of around 20% with radiosonde humidities and scatterometer winds having average benefits of 7% and 2% respectively. The low benefit of scatterometer winds is curious considering the relatively large benefit from the less abundant conventional surface data over the oceans. Some possible reasons for the discrepancy are given in Section 6.

Unfortunately we are unable to assess specifically the benefit from ship based radiosonde reports. The individual benefits recorded for radiosonde winds and temperatures in Table 6b will include contributions from land stations near to the impact source, particularly when the impact source is in a coastal region. Consequently the large average individual benefit from radiosonde winds cannot be considered representative of the impact of the relatively small number of ship-based radiosondes.

(c) Summary of the 90% subset for all cases

Typically, the major part of the impact is contributed by the rank 1 and rank 2 observations from the 90% subset. We therefore refer to the ranks 1 and 2 as playing key rôles in the benefit and the ranks 3 and 4, when required, as playing important support rôles. Justification for this distinction is shown in Table 7, which shows the average increment in benefit obtained by adding observations to the assimilation in order of their rank. Ranks 1 and 2 contribute 85% of the ALL OBS benefit on average, with ranks 3 and 4 incrementing the benefit by a considerably smaller margin than rank 2 ($\sim$5% compared to 19%).

(i) North American Cases: A summary of the 90% subsets found for the 10 North American cases is given in Fig. 6a, the histograms show the number of times that a data type was included in the subset at a given rank. The abundance of radiosonde and aircraft observations over North America is again reflected in their high score. Wind information from both these data types are included in the 90% subset in 6 out of the 10 cases, and each play a key rôle in 4 instances. Radiosonde temperatures and aircraft temperatures are included in 3 and 4 of the cases, respectively. Both radiosonde and aircraft temperatures play key rôles in 3 cases. The results confirm that the radiosonde and aircraft networks are key elements in the North American observing system, contributing to cases of major impact with similar frequency. Fig. 6a also confirms the conclusion inferred from the results on individual benefit (Sections 5(a)&(b)) that the wind information contributes more frequently than the temperature information.

Satellite temperatures have 2 inclusions, one in a key rôle and one in a supporting rôle. However, as discussed previously satellite temperatures are not used over land areas below 100 hPa (Table 3), and consequently have little opportunity to contribute to the analysis over North America.

Surface data and cloud-track winds each have 3 inclusions distributed between key and supporting rôles. Radiosonde humidity data have played an important rôle in only 1 case. No examples of a significant impact from scatterometer wind data were found in the North American cases. However, since these data are only available over the ocean surface they will have little opportunity to contribute.

(ii) Oceanic Cases (North Pacific and North Atlantic): Fig. 6b shows combined results from the 7 North Atlantic cases and 3 North Pacific cases. The abundance of aircraft data in these regions, relative to other conventional observation types, is reflected in the high score for aircraft winds which contribute in 9 of the 10 cases and play a key rôle in 5 cases. The temperature part of the aircraft observations appears to be much less beneficial, contributing only once, and that in a supporting rôle. The low frequency of impact for temperature reports contrasts with the results for North America (Fig. 6a) where aircraft winds and temperatures contribute with similar frequency. These results support the findings for individual impact (Section 5(a)&(b)) and add weight to our previous inference that temperature information is more useful if added in the lower rather than upper troposphere.

Satellite temperature soundings are also used in large numbers over the oceans, however they were included in the 90% subset in only 3 cases, and only once in a key rôle. The lack of impact found from this data type may reflect the fact that our evaluations are focused on synoptic-scale systems (see discussion in Section 6(d)). Eyre et al. (1993) have shown that satellite temperature soundings have their main impact on scales larger than the synoptic-scale. Furthermore, in this study the soundings were assimilated in the form of statistically retrieved layer-mean temperatures, rather than by making direct use of the radiance information. Eyre et al. (1993) and Gadd et al. (1995) have shown that greater benefits are possible from direct use of the radiance information. Satellite cloud-track winds have a similar frequency of benefit to the satellite temperature soundings having been included in the subset in 2 of the 10 cases, achieving rank 1 in one case.

Surface data have been included in the 90% subset in 5 of the 10 cases, playing a key rôle in the impact in each case. This contrasts with the results over North America which indicate a relatively less prominent rôle for surface data. The results suggest that the conventional surface observation network plays a very important rôle in the analysis of synoptic-scale systems over the oceans, more important than the satellite layer-mean temperature soundings, and the cloud-track winds.

Scatterometer wind data have not been included in the 90% subset in any of the 8 oceanic cases for which they were available. This seems surprising in light of the high frequency of impact from conventional surface wind and pressure observations, some possible reasons for the discrepancy are discussed in Section 6.

6. SUMMARY AND CONCLUSIONS

Using a method of multiple case study assessment, the benefit of observations to NWP forecasts has been measured according to their impact when used alone in the assimilation (the "individual" benefit) and also according to the number of times they belong to the smallest subset of data types required to achieve 90% or more of the benefit obtained with all the available data. Twenty forecast cases have been studied, each selected for showing a marked sensitivity to initial data. In half the cases the impact source was located over North America, in the other half the impact source was over the North Atlantic or North Pacific.

The conclusions of the study should be considered in light of the scope of the method, which is discussed in Section 6(d).

(a) Summary of results for North America

Observation benefits to global model forecasts of PMSL, based on 10 cases over North America, are summarised below.

- The key rôle of radiosonde and aircraft observations in NWP analyses over North America is confirmed. These networks contribute most often and with similar frequency.
- Surface data (PMSL reports) and cloud-track winds play the most important support rôles.

(b) Summary of results for Oceanic Cases

Observation benefits to global model forecasts of PMSL, based on 7 cases over the North Atlantic and 3 cases over the North Pacific, are summarised below.

- Aircraft winds contribute most frequently, and considerably more frequently than aircraft temperatures.
- Conventional surface data (PMSL and winds) play a key rôle in these relatively data sparse regions.

(c) Discussion of results

In this section we summarise some further findings and add some comments to the main results given in the previous sub-Sections.

(i) Wind information contributes more frequently than temperature information (Figs.6a&b).

(ii) Temperature information is most beneficial if added in the lower troposphere. This finding could have implications for the design of future temperature sounding instruments. It would be worthwhile to perform Observation System Simulation Experiments to test this result.

(iii) The fact that radiosonde information contributes as frequently as aircraft information over North America (Fig.6a), despite the greater numbers of the latter, may reflect the advantages of profile information over single-level reports. Aircraft reports are most numerous at cruise-levels, where they will often be too high to give a good description of features important for cyclogenesis (e.g. regions of tropopause descent). At low and mid-levels aircraft reports are confined to the vicinity of airports, and give less coverage than the current radiosonde network. Alternatively, the similar impacts from the two networks might be explained if the high density of upper-level aircraft reports results in a degree of redundancy which, when coupled with the inferior coverage at low-levels, leads to an overall data impact similar to that of the less abundant but more evenly distributed (in 3 dimensions) radiosonde network.

(iv) The few cases of benefit found from satellite temperatures partly reflect the fact that statistically retrieved temperatures were assessed. Use of direct radiance information from TOVS has been shown to give significantly more impact than

statistical retrievals (e.g. Gadd et al., 1995). Kelly (1997) also finds relatively little impact from TOVS in the northern hemisphere, though significant impacts were found in the tropics and southern hemisphere.

(v) The high frequency of benefit found for land-based radiosondes suggests that increased deployment of ship-borne radiosondes (ASAPs), if made in sufficient numbers, may bring considerable benefits to NWP forecasts. Graham (1990) and Heming (1990) have documented individual cases of useful ASAP impact. The substantial impact from land-based radiosonde temperature profiles indicates that global coverage from forthcoming high resolution temperature sounders (e.g. IASI) will bring considerable benefits (which may lessen the requirement for more ASAPs).

(vi) No significant contributions from scatterometer 10m wind data were recorded. This contrasts with the high frequency of impact from conventional oceanic surface data (Fig. 6b). It should be recalled that the conventional surface reports include PMSL measurements in addition to 10m wind, and thus may be expected to deliver greater impact. However, the fact that the far greater abundance of scatterometer data (Table 1) does not appear to compensate for lack of accompanying mass observations, suggests that there may be scope for improving the assimilation of scatterometer information. Note that significant positive impact from scatterometer winds has been found for the Southern Hemisphere (see e.g. Bell, 1994). Moreover the magnitude of the impact was increased by a revision to the assimilation scheme (active for the cases in this study) which introduced assimilation of balanced surface pressure and potential temperature increments derived from the wind increment field (Andrews and Bell, 1998).

The use of model forecast fields to aid the removal of ambiguity in the scatterometer wind retrievals may also contribute to the relatively low frequency of impact found. Observation impacts are most likely in cases where there are large errors in the background field (i.e. where the scope for data to correct the model is largest). Unfortunately, because of the dependency of the wind solutions on the model background, such cases also correspond with cases in which selection of the correct solution (rather than one which agrees with the erroneous model background) is most difficult.

(vii) Although humidity observations can improve forecasts of PMSL by improving the distribution of latent heating, radiosonde humidity profiles appear to have had little impact on the forecasts studied here. However, using a similar method of serial case studies, radiosonde humidity profiles have been found to be very beneficial for short-range mesoscale model forecasts of rain accumulation (e.g. Anderson et al., 1998a).

(d) Discussion of the method

The method employed has the advantage of assessing observation benefit to forecasts of meteorological systems of prime importance to operational meteorology. The results therefore provide a complement to those which assess "average" performance through statistical assessment. The problems associated

with the representativeness of case study assessments have been addressed by aggregating results over 20 cases. There is agreement between the results of this study and those of statistical data-denial studies (e.g. Unden, 1997; Kelly, 1997) that radiosondes are currently the most useful northern hemisphere observing system. Data-denial studies also provide further evidence of the major benefits provided by aircraft reports. Over North America, for example, Unden (1997) found impact from aircraft reports equivalent to a gain in forecast skill of ~3/4 day - comparable to that obtained from the radiosonde network. On a hemispheric scale, however, data-denial studies (e.g Atlas 1997; Kelly, 1997) indicate the impact from aircraft reports is substantially less than that of radiosondes. The relatively greater impact from aircraft reports found in this study suggests that, because of the tendency for a densely clustered distribution, they contribute frequently to the correction of small-scale details in the analysis - which are likely to be important for forecast accuracy in localised events such as those considered in this study - but less frequently than the more distributed radiosonde network to the analysis of larger-scale, more slowly varying features.

The general agreement between the multiple case study and statistical methods on the impact of the radiosonde and aircraft networks suggests that the 20 cases provide a useful level of representativeness; the agreement lends confidence to our assessments for the other observation types evaluated.

Some factors that define the scope of the assessment are listed below.

(i) Only cases of impact on systems originating over the North American continent and the North Atlantic and North Pacific oceans have been considered. Although this limits the generality of the results, it is possible to make inferences for other regions, as is discussed in Section 7.

(ii) Only benefit to forecasts of a single variable (PMSL) using a single model resolution (~90 km) , has been considered. This will clearly influence the perceived observation value; a given observation type may be much more beneficial for forecasts of a different variable with model of different resolution (see point (vii) of Section 6(c)).

(iii) The method is weighted towards assessing observation impact on systems of synoptic-scale at the expense of larger-scales. This follows for two main reasons. Firstly, the case selection method, which relies on the absolute amplitude of the data impacts, will tend to filter out cases of impact on large-scale systems (which will tend to be of relatively low amplitude). Secondly, the method favours observations which sample systems that can move or develop substantially on a timescale of the 15-hr assimilation period (i.e. synoptic-scale systems). Observations which sample mainly large-scale systems, which tend to vary little over 15 hours, will have less opportunity to demonstrate an impact. The method may therefore underestimate the overall benefit of the satellite temperature soundings which have low vertical resolution but extensive horizontal coverage, and therefore tend to have their largest impact at scales larger than the synoptic-scale. The method may also underestimate the impact of temperature observations in general, since theoretical studies indicate that model fields take longer to adjust

to temperature data (e.g. Kalnay et al., 1985).

It should be recalled that this investigation is based on studies of northern hemisphere cases. The land areas of the northern hemisphere are relatively rich in conventional observations and, as a result, NWP model analyses are of sufficiently high accuracy to make further improvements from new systems difficult to demonstrate (though improvements have been achieved by more sophisticated observation processing (see e.g. Gadd, 1995; Kelly, 1997)). Over the extensive oceans of the southern hemisphere the conventional observing network is extremely sparse, and remotely sensed data from satellites play a crucial rôle. For example Kelly (1997) has shown a southern hemisphere benefit from satellite temperature soundings, while Bell (1994) shows a substantial impact from scatterometer winds on forecasts with the UK Met Office model (though Gaffard and Roquet (1995) found neutral impact using the ECMWF model).

Strictly, our results are specific to the methods of observation processing and assimilation in use at the UK Met. Office over the duration of the study, although consistency with the results of studies using other assimilation schemes (e.g. the study of Unden (1997) using the ECMWF model) suggest that there is a useful degree of generality in the results. It should be borne in mind, however, that observation impacts reflect the combined effectiveness of the observations and the assimilation scheme, and that care should be exercised when seeking to draw conclusions about the observations alone.

The work of Rabier et. al (1996) has brought attention to the fact that extremely small changes to the initial analysis, if made in a dynamically "sensitive" region, can result in large differences in the forecast evolution. The magnitude of the analysis changes required are typically smaller than the observation error for most systems. Consequently, a proportion of the impacts from single-data types might be attributable to chance projection of random "noise" associated with the assimilation process on to an unstable atmospheric mode, rather than from any true signal from the observation assimilated. If this were so, the relative magnitude of "individual" impacts in a given case (e.g. as in the example of Table 4) might not be robust to small changes in the model formulation. As a first order check for this possibility, Case 4 was run a second time after a number of updates to the model physics had been implemented in the interim. It was found that, although the percentage "individual" impacts were not identical to those of the original run, the differences were sufficiently small for the ranking order of the first 4 observation types to remain unchanged, implying that (in this case at least) the impact results are robust to minor changes in the NWP model.

7. RECOMMENDATIONS FOR THE NORTH ATLANTIC/EUROPEAN AREA

The radiosonde network plays a key rôle in NWP analyses and should be retained where possible. The profile format of the information provided by these reports may add significantly to their value for forecasting cyclogenesis events.

The substantial benefits derived from the aircraft network over North America suggest that enhancing the aircraft network over the North Atlantic and Europe would yield substantial benefits to forecasts for the European area. In

addition to reports from cruise levels, reports made during climb and descent phases over Europe would also be beneficial. Enhancement would be assisted by more widespread use of automatic observation and transmission technologies.

High resolution data from below aircraft cruise levels is badly needed over the North Atlantic. The potential value of such data may be inferred from the substantial benefit obtained from aircraft temperatures over North America, much of which appears to derive from data in low-to-mid levels. Our results imply that TOVS data, which sample these levels, are of limited utility in resolving rapidly evolving synoptic detail (though they may be important in maintaining the general quality of the model background). High resolution soundings will not be available before 2002, when the IASI (Improved Atmospheric Sounding in the Infra-red) instruments are scheduled to become operational (though the ATOVS data, scheduled to come on line in 1998, will provide better moisture sounding and improved coverage in cloud).

The high frequency of impact from wind information in the free atmosphere particularly over oceans suggests that considerable benefits could accrue from greater coverage of satellite pattern-tracking winds. Increased coverage, extending to cloud-free regions, may be achieved through tracking patterns in water vapour channel imagery - however difficulties with height assignment of the derived winds currently limit their usefulness (see e.g. Tomassini *et al.,* 1997).

A major opportunity for improving the global observing system lies in the development of space-borne Doppler wind lidar instruments, which could provide future operational global coverage of wind profiles in regions free of thick cloud (e.g. ALADIN, Betout et al., 1989). Such instruments will be expensive to develop compared with passive temperature sounders, but the advantages of wind profiles compared to temperature profiles shown in this and other studies suggests that the benefits to NWP may be significantly greater.

In the meantime improved observation can be approached using conventional systems. Our results show that in the absence of good coverage in the middle to lower troposphere, surface data can deliver important impacts. Increasing the coverage of surface information (e.g. buoys, ships) might be worthwhile as an intermediate step to obtaining more extensive observation of the boundary layer and free atmosphere (Grant et al., 1996 describe a striking example of a positive impact from North Atlantic drifting buoys on a forecast with the UK Met Office Limited Area Model). Our results suggest that research into more effective ways of using scatterometer wind information over the ocean surface is required to extract the full potential of the data. Improved observation of the free atmosphere may be achieved by increased use of ship-borne radiosondes (ASAPs). The substantial impacts found from land-based radiosonde profiles suggest that if deployed in sufficient numbers, ASAPs may be bring substantial improvement to forecasts.

The concept of an "adaptive" observing system (Synder, 1996) is gaining ground in some National Meteorological Centres. The feasibility of such systems is currently being studied using data from the Fronts and Atlantic Storm Track Experiment (FASTEX) (Joly, et al., 1997). For example, Anderson et al. (1998b) and Graham et al. (1997) present case study evidence that dynamically "sensitive" areas can be identified in a timely manner using objective techniques, and that sampling such areas with dropsondes can deliver significant benefit to NWP

forecasts. An adaptive observing system, possibly using Unmanned Airborne Vehicles (UAVs) would target regions where data are most needed and could prove cost-effective.

The above recommendations are summarised below.

- Retain the current radiosonde network.
- Acquire more aircraft data over Europe and North Atlantic.
- Consider deployment of more ship-borne radiosonde ascents (ASAPs) and surface observations (e.g. drifting buoys) in the North Atlantic.
- Improve coverage of upper-air wind observations through water-vapour pattern tracking winds.
- Investigate ways of making better use of scatterometer wind information in the model assimilation.

- Continue studies on the feasibility of an "adaptive" observing system.

Acknowledgements

We would like to thank Roger Grant, John Eyre, Andrew Lorenc and Bob Lunnon for guidance at various stages in this study; and Stuart Bell, Bruce Ingleby, Colin Parrett, David Robinson and Mussadiq Ahmed for help and advice on the assimilation aspects of the work.

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	NORTH PACIFIC 180°-135°W	NORTH AMERICA 120°-75°W	NORTH ATLANTIC 55°-10°W	EUROPE 0°-45°E
TOVS	3550	350	**5750**	775
AIRCRAFT	400	**5360**	315	75
RADIOSONDE	180	2520	165	2985
SURFACE	150	630	280	**3300**
CLOUD TRACK WINDS	60	10	130	35
SCATTEROMETER 10m WINDS	**3600**	0	2900	465

Table 1: Example of the numbers of observations (rounded to nearest 5) used in a 15-hour assimilation period (between 30°N-60°N, below 100 hPa and for four longitude intervals). The numbers are those for Case 7 of the study, except for scatterometer 10m winds for which the numbers are for Case 20. The largest numbers in each region are in bold.

Case No.	DATE/HR OF FORECAST VERIFICATION	LOCATION OF IMPACT AT ASSIMILATION	MAIN FEATURE IMPROVED IN THE T+60 FORECAST
1	19:09:93 00GMT	N. ATLANTIC	Trough over Mediterranean
2	26:10:93 00GMT	N. AMERICA	Low over east coast of North America
3	08:12:93 00GMT	N. PACIFIC	Low over Western Canada
4	31:12:93 00GMT	N. AMERICA	Suppression of spurious low affecting UK in T+72 forecast
5	05:01:94 12GMT	N. AMERICA	Low over east coast of North America
6	21:01:94 00GMT	N. ATLANTIC	Suppression of spurious trough over Denmark in T+72 forecast
7	10:02:94 12GMT	N. AMERICA	Low over east coast of North America; high over Great Lakes
8	09:07:94 00GMT	N. AMERICA	Low near Great Lakes
9	17:10:94 00GMT	N. ATLANTIC	Suppression of spurious trough over western UK in T+72 forecast
10	02:11:94 12GMT	N. AMERICA	Low over east coast of North America
11	03:11:94 12GMT	N. PACIFIC	Low over NW Canada/Alaska
12	26:12:94 12GMT	N. PACIFIC	Surface trough/ridge pattern over and west of Hudson Bay
13	05:01:95 12GMT	N. AMERICA	Surface trough/ridge pattern over Norway
14	02:02:95 00GMT	N. ATLANTIC	Trough over the North Sea
15	16:05:95 12GMT	N. ATLANTIC	Position of large low near UK
16	21:12:94 00GMT	N. AMERICA	Intensity of low near UK improved (weakened)
17	07:11:94 12GMT	N. AMERICA	Intensity and position of low over Newfoundland
18	14:08:94 00GMT	N. ATLANTIC	Low over Norway and Sweden
19	24:02:95 12GMT	N. AMERICA	Suppression of spurious low over UK and Low Countries
20	29:12:95 00GMT	N. ATLANTIC	Trough affecting Ireland

Table 2: Date and classification of the twenty cases studied. A brief description of the main synoptic feature improved in the T+60 forecast is also given.

No.	OBSERVATION TYPE	ABR.	REMARKS ON GLOBAL MODEL USAGE		
1	RADIOSONDE WINDS	RsW	Includes PILOT reports		
2	RADIOSONDE TEMPERATURES	RsT	-		
3	RADIOSONDE HUMIDITIES	RsH	-		
4	AIRCRAFT WINDS	AcW	-		
5	AIRCRAFT TEMPERATURES	AcT	-		
6	SURFACE OBSERVATIONS	SFC	Over land: PMSL reports only Over ocean: PMSL and wind observations from some systems		
7	SATELLITE TEMPERATURE SOUNDINGS	SaT	TOVS data: Form used = 120 km and 500 km NESDIS retrievals. Not used below 100 hPa over land, or below 850 hPa over sea (north of 30S)		
8	CLOUD-TRACK WINDS	CTW	Observations not used in Northern Extratropics (20-90N)		
				Before 2/8/94 (cases 1-8)	After 2/8/94 (cases 9-20)
			GMS	Above 500 hPa	Below 500 hPa (over land)
			METEO - SAT	Above 500 hPa (over land)	Below 500 hPa (over land)
			GOES	Above 500 hPa (over land)	Below 500 hPa (over land)
			INSAT	All	All
9	SCATTEROMETER 10M WINDS	SCT	Observation of sea areas only.		

Table 3: Data types assessed and remarks on their use in the UK Met. Office Global Model. Details of a change, introduced during the course of the study, in the operational use of cloud-track winds are included in row 8.

OBSERVATION TYPE USED	RMSE (PMSL)	% OF ALL OBS BENEFIT
ALL OBS	2.34	100
AIRCRAFT WINDS	6.51	50
RADIOSONDE WINDS	6.99	45
AIRCRAFT TEMPERATURES	7.58	38
RADIOSONDE TEMPERATURES	8.28	29
SATELLITE TEMPERATURES	9.34	17
SURFACE DATA	10.13	7
RADIOSONDE HUMIDITIES	10.32	5
CLOUD TRACK WINDS	10.61	2
SCATTEROMETER 10M WINDS	10.64	1
NO OBS	10.76	-

Table 4: Example table of individual benefits of observation types (taken from Case 10, North America 02/11/94). Percentage of ALL OBS benefit is defined as;
$100 \times$ [RMSE(NO OBS) - RMSE(OB TYPE)]/[RMSE(NO OBS) - RMSE(ALL OBS)].
The area over which the RMSE is calculated is shown in Fig. 3b.

	OBSERVATIONS USED	% OF ALL OBS BENEFIT
1	AIRCRAFT WINDS	50
2	1 + RADIOSONDE WINDS	57 (+07)
3	2 + AIRCRAFT TEMPERATURES	73 (+16)
4	3 + RADIOSONDE TEMPERATURES	87 (+14)
5	4 + SATELLITE TEMPERATURES	89 (+02)
6	5 + SURFACE	99 (+10)

Table 5a. Step 1: Data types are added to the assimilation in order of their individual impact (Table 4) until 90% or more of the ALL OBS impact is achieved. The impact is measured in terms of the percentage of the ALL OBS - NO OBS error reduction. Impact increments are shown in brackets.

	OBSERVATIONS USED	% OF ALL OBS BENEFIT
7	6 - SATELLITE TEMPERATURES	94
8	7 - RADIOSONDE WINDS	95
9	8 - SURFACE	84

Table 5b. Step 2: Data types giving the lowest additional benefit (e.g. in this example, satellite temperatures, radiosonde winds and surface data - cf. Table 5a) are withheld from the assimilation to see if 90% of the ALL OBS impact can be achieved without them.

RANK 1	AIRCRAFT WINDS
RANK 2	RADIOSONDE TEMPERATURES
RANK 3	SURFACE
RANK 4	AIRCRAFT TEMPERATURES

Table 5c. The final subset is ranked in order of cumulative benefit. Rank 1 is the data type giving the largest individual benefit, rank 2 delivers the largest increment to rank 1, etc.

				OBS TYPE					
CASE	RsW	RsT	AcW	AcT	SaT	CTW	SFC	RsH	SCT
2	35	54	31	6	NEG	15	13	0	N/A
4	45	33	6	91	27	42	NEG	9	N/A
5	56	11	76	73	NEG	18	36	7	N/A
7	49 (51)	56	13	7	21	15	16	3	N/A
8	72	9	33	NEG	9	NEG	17	20	0
10	45 (30)	29	50	38	17	2	7	5	1
13	89 (85)	NEG	NEG	NEG	63	NEG	5	NEG	NEG
16	41 (40)	NEG	64	41	NEG	37	25	4	1
17	35 (35)	15	75	3	NEG	10	22	29	3
19	18 (18)	30	29	85	20	NEG	39	NEG	NEG
AVGE	49	24	38	34	16	14	18	7	1
NEG	-	**2**	**1**	**2**	**4**	**3**	**1**	**2**	**2**

Table 6a: Individual benefits for 10 North American case studies. Benefit is expressed as a percentage of the ALL OBS benefit. The average benefit over all cases, and the number of times the data type delivers a negative impact when used alone are also shown (negative impacts are counted as zero benefit when calculating the average).
N/A indicates that no observations of that type were available for the experiment. Values in brackets in the second column indicate impacts when all PILOT wind reports are withheld (see text).
Abbreviations used for the observation types are;

RsW/T/H = Radiosonde Winds/Temperatures/Humidities
AcW/T = Aircraft Winds/Temperatures
CTW = Cloud-Track Winds
SFC = PMSL and, over the oceans, surface winds
SaT = Satellite Temperature Soundings (120km&500km)
SCT = ERS-1 Scatterometer 10m winds

				OBS TYPE					
CASE	RsW	RsT	AcW	AcT	SaT	CTW	SFC	RsH	SCT
1 (A)	40	NEG	51	37	26	57	NEG	6	3
3 (P)	12	9	67	3	NEG	15	61	0	NEG
6 (A)	77	NEG	66	NEG	14	9	NEG	0	N/A
9 (A)	62	NEG	119	#	NEG	71	NEG	33	#
11 (P)	30	5	20	10	26	25	38	NEG	5
12 (P)	61	31	9	2	15	NEG	50	NEG	NEG
14 (A)	21	20	23	7	53	10	NEG	NEG	NEG
15 (A)	39	18	5	0	7	NEG	63	6	0
18 (A)	36	18	34	NEG	30	5	34	11	0
20 (A)	46	37	42	19	18	3	41	16	9
AVGE	42	14	44	9	19	20	29	7	2
NEG	-	**3**	-	**2**	**2**	**2**	**4**	**3**	**3**

Table 6b: As Table 6a but for the Oceanic cases. An "A" after the Case No. indicates the case was of North Atlantic origin, a "P" indicates a North Pacific origin. In one case technical problems lead to missing results (indicated by "#").

OBSERVATIONS USED (20 cases)	AVERAGE BENEFIT (%)	
	Increment	Total
RANK 1	66	66
RANKS 1 + 2	19	85
RANKS 1 + 2 + 3	05	90
RANKS 1 + 2 + 3 + 4	04	94

Table 7: Average increment in benefit obtained by adding observations in order of their rank.

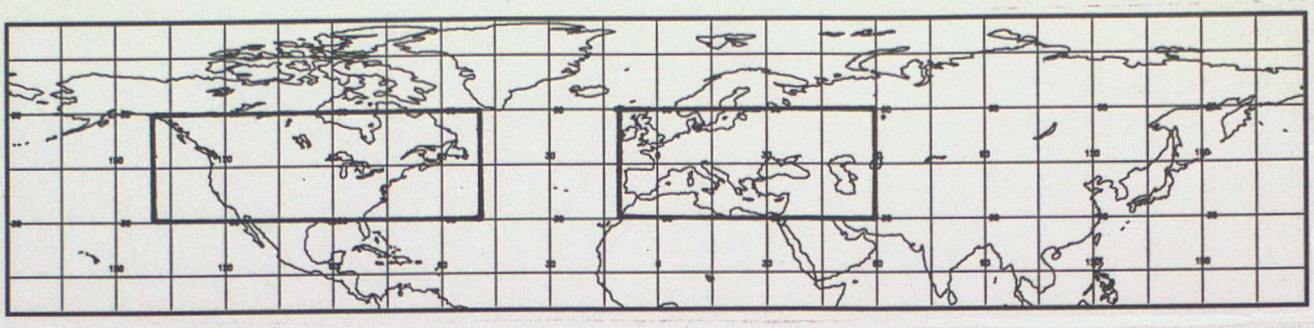


Fig. 1: The case selection areas over North America and Europe/Western Asia.

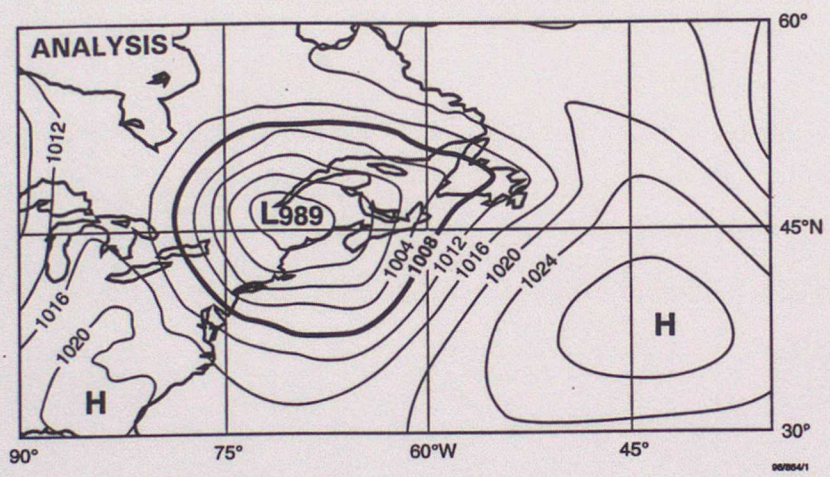


Fig. 2: PMSL analysis for 12GMT 2 November 1994. Contour interval = 4 hPa, the 1008 hPa contour has been highlighted.

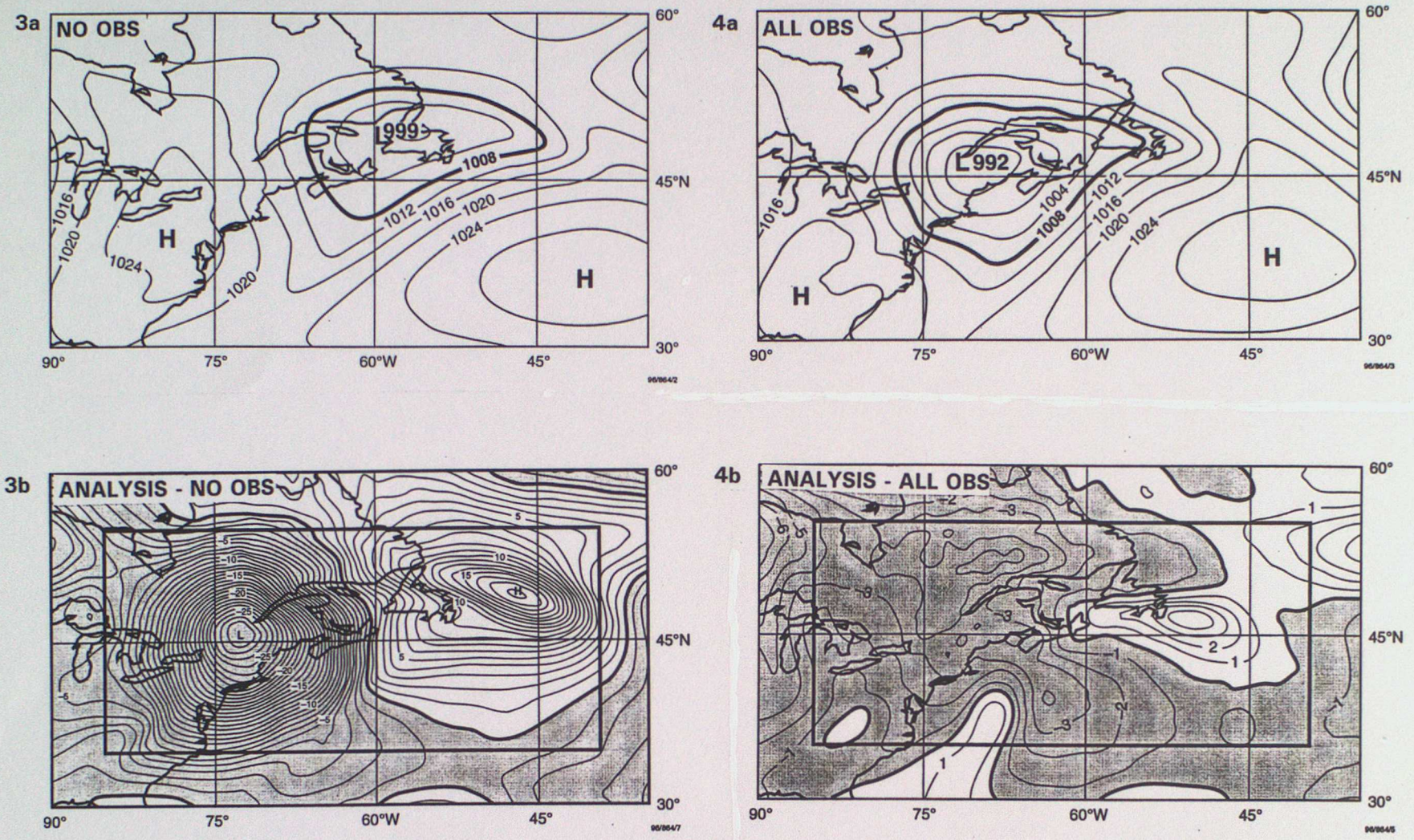
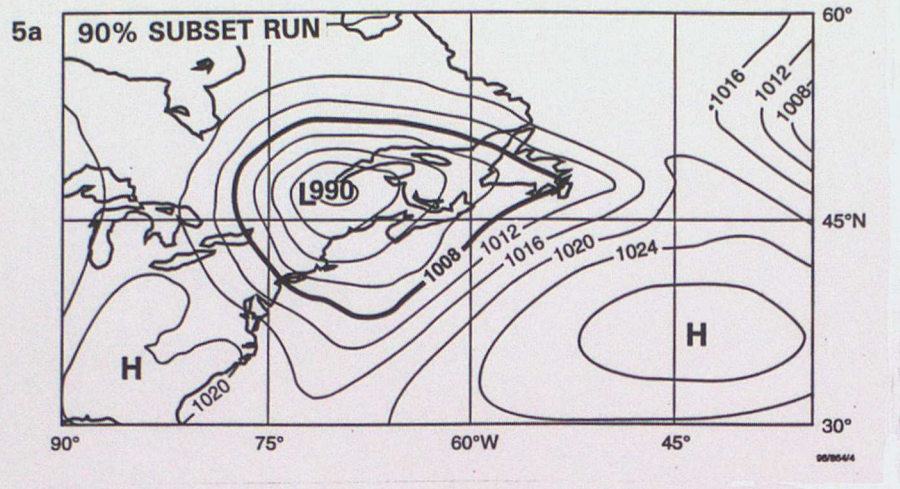


Fig. 3a: T+60 forecast for PMSL from the NO OBS control, valid at 12GMT 2 November 1994. Contouring conventions as Fig.2

Fig. 3b: The error in the T+60 NO OBS forecast (ANALYSIS - NO OBS). Contour interval = 1 hPa; the zero contour has been highlighted and negative values are shaded. The area over which the rms error is calculated (see Table 4) is shown.

Fig. 4a: As Fig.3a, but for the ALL OBS control.

Fig. 4b: As Fig.3b, but for the ALL OBS control.



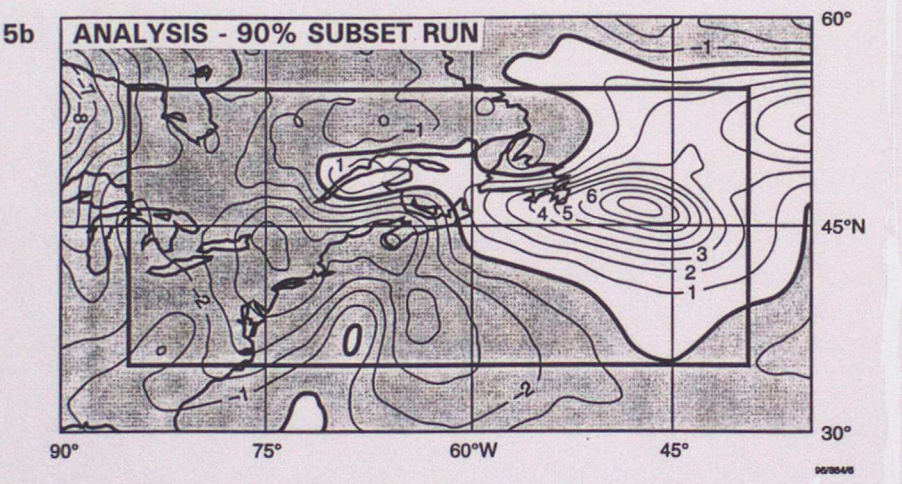


Fig. 5a: As Fig.3a, but for the 90% subset run (in which only the data types included in the 90% subset are presented to the assimilation).

Fig. 5b: Error in the 90% subset run (Fig. 5a). Contouring conventions as Fig. 3b.

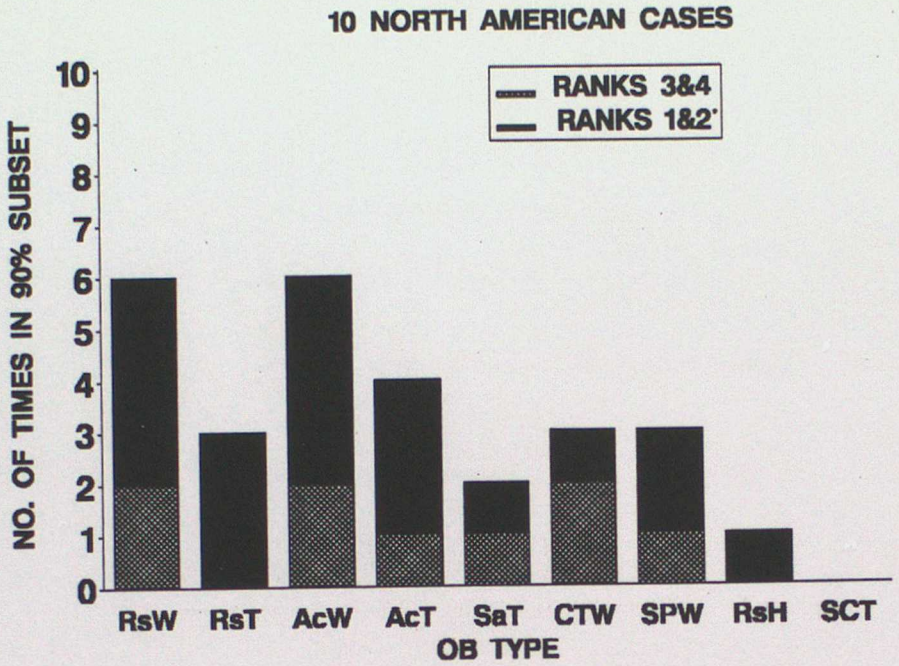


Fig. 6a: Histogram for the 10 North American cases showing the number of times a data type qualified as a member of the 90% subset. Dark shading represents the number of times the data type qualified at Rank 1 or Rank 2; hatched shading the number of times at Rank 3 or Rank 4.
RsH/W/T = Radiosonde humidities/winds/temperatures; AcW/T = aircraft winds/temperatures; SaT = satellite temperature soundings (statistical retrievals); CTW = cloudtrack winds; SCT = scatterometer 10m winds; SPW = surface pressure and conventional wind observations (wind observations over oceans only).

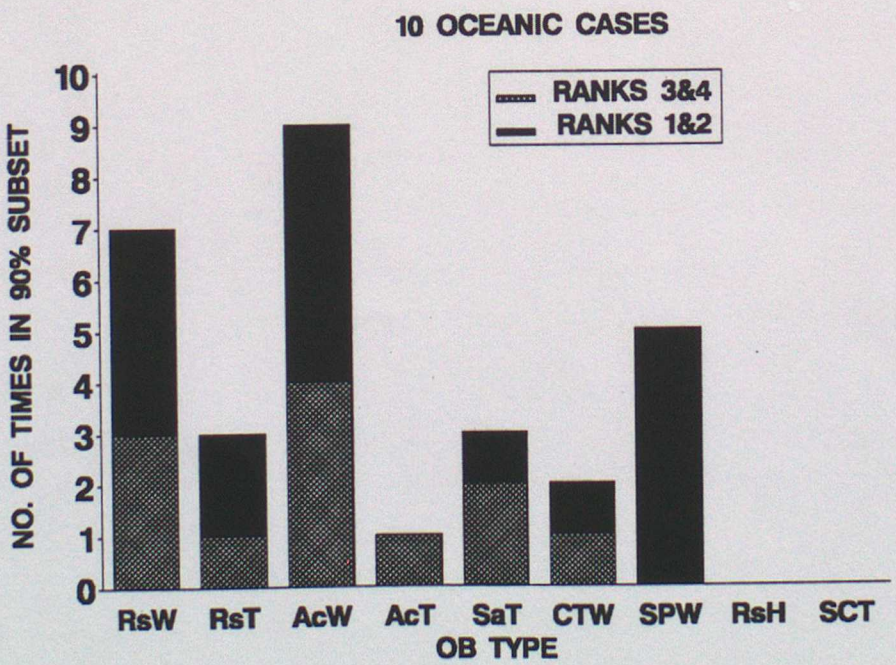


Fig. 6b: As Fig.6a, but for the 10 oceanic cases. The bars for radiosonde observations are not representative of the small numbers of shipbased ascents (see text).